Energy Policy 113 (2018) 376–385

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

A 'Regional Energy Hub' for achieving a low-carbon energy transition

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ARTICLE INFO

Keywords:
Electricity markets
Transmission investment
Regional energy hub
Low-carbon energy economy

ABSTRACT

The transition to a low-carbon energy economy will remain a cornerstone of national energy policies of countries committed to the climate change accord for decades to come. We think that transmission investment is one key policy instrument amongst other to help with this transition. We propose an enhanced role for investing in transmission capacity for inter-regional trade to allow effective fuel switching among countries through a physically connected market. We develop a conceptual framework of "Regional Energy Hubs" and propose a cost minimization model in support of a transmission investment strategy that integrates: (i) a key geopolitical parameter for countries that are geographically close in a region but under different political jurisdictions, judged as stable and receptive to firm trading arrangements, (ii) an economic parameter related to the fuel mix where the differences in a country's supply and demand characteristics are significant enough for allow mutual benefits to be realized through cost reduction, (iii) an environmental parameter linked to a country's carbon intensity that could benefit from the resources of a neighboring jurisdiction with lower intensities, and (iv) a financial parameter for each country within a region capable of attracting investment capital. A connected 'Regional Energy Hub' offers large economic and environmental benefit for transition to a low-carbon energy economy.

1. Introduction

Prior to liberalization of electricity markets, transmission investment decisions often resulted in overcapacity of the built system (Joskow, 2006). Transmission investment decisions were primarily based on matching the demand (load) with generation requirements to maintain the system reliability (Joskow et al., 2008). Currently, decision making process for transmission investments is still heavily influenced by the monopolistic nature of the transmission system infrastructure. The dichotomy arises from a deregulation effort that was primarily confined to the generation and distribution of the regulated utility assets, but transmission system ownership remained as a regulated monopoly and this in turn caused transmission investments to lag behind the generation investment (i.e., centralized transmission planning versus decentralized generation investments) (Pfeifenberger, 2012). Although several options ranging from pure merchant to fully regulated options were developed to incentivize investments, the transmission system could not keep up with the demand and new emerging generation capacity with increasing share of renewable generation with variable and intermittent output on the system. Transmission investments initially flourished in the electricity markets in several countries (e.g., United Kingdom –UK, United States –US, Norway, Sweden) led by a few transmission system operators (TSOs) (e.g., National Grid, Pennsylvania-New Jersey-Maryland –PJM, Stattnet, Swenska kraftnat, respectively), but further developments of the wholesale markets have not been robust with the consequences that congestion is notable, the investment and integration pathways are unclear and regional capacity planning issues among the markets and the regions are emerging (Ramachandra, 2009).

In this paper, we propose a new perspective on regional transmission investments in the evolving organized electricity markets and energy policy requirements. Besides providing engineering reliability and facilitating economic trade as the two major objectives of transmission investments (Conejo et al., 2016), we propose the concept of a 'Regional Energy Hub' (REH) that integrates key geopolitical, economic, environmental and financial factors to foster investment decisions for transmission adequacy. A REH enabled through requisite transmission capacity becomes an investment option for regional optimization of diverse supply resource needs to come into play from similar concepts introduced earlier (FERC, 2011; OFGEM, 2010; EC). We argue that transmission has a positive and increasing role in the evolving convergence of climate change policies as they relate to connected markets, integration of large amounts of renewable generation and removal of congestion bottlenecks in the system. The goal is to optimize

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https://doi.org/10.1016/j.enpol.2017.10.044
Received 7 February 2017; Received in revised form 19 September 2017; Accepted 26 October 2017
Available online 21 November 2017
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underutilized generation capacities over a wide geographic area through additional transmission interconnectors and to assess the benefits from a regional perspective that would support a low-carbon energy economy across several independent jurisdictions and countries (Ochoa and van Ackere, 2015; Aguado et al., 2004; EPRI, 2014).

We describe a novel framework for enabling a robust basis for transmission investments that take into account most considerations/opportunities for optimization on a regional basis, but excluding stochasticity, robustness from optimization perspective and risk-neutrality issues. Therefore, the objective of this paper is to:

i. develop a definition of the concept of REH to improve and verify transmission investments against a set of considerations that include the geopolitical, economic, environmental and financial perspectives (i.e., the REH factors),
ii. develop a framework for identifying the REH and the key factors so that the benefits for the region are better ascertained and measured,
iii. develop a generic mathematical model based on (i) and (ii) above, and to apply this model to the evaluation of a case study for the Romania-Turkey transmission investment,
iv. quantify benefits for the defined region according to the REH factors.

We build upon the existing body of knowledge on transmission investment approaches to help clarify the convergence of two high-level policy goals: energy policy as an integral part of climate change mitigation and adaptation strategies. The REH approach has the potential to provide key insights on how the transmission investments and effective pathways for enhanced electricity trade can pave the way for a broader de-carbonization strategy at a lower cost to all consumers.

More importantly, we think that REH framework could serve as a platform to (i) identify the need for further investigation into adaptation strategies such as transmission planning, generation expansion (i.e. renewables), demand side response, or storage; however, the purpose of this study is not to investigate these adaptation strategies individually, which is already studied extensively, but (ii) to capture and consider them from a regional perspective so that transition to low-carbon energy economy is effective.

The paper is organized as follows: Section 2 reviews the literature on transmission investment in electricity markets, as well as the issues, challenges and barriers of the current state of the art. Section 3 defines the research problem and the objective of this study, whereas Section 4 frames the methodology in approaching the research problem. Section 5 concludes with a case study for Turkey-Romania interconnector investment decision where REH is applied and benefits are quantified.

2. Background

As the market economy has evolved around the world, many countries have opted for liberalization of their electricity market starting as early as 1980s in Chile and the UK (Pollitt, 2004). By 1990s, many countries have had functioning liberal electricity markets (Stridbaek et al., 2006).

Prior to the liberalization of the electricity markets, states regulated the electricity value chain. It had a monopolistic model from generation to transmission such that they were state (publicly) owned generators, transmission and distribution companies, and no functioning wholesale or retail market. In this context, the transmission investment planning and decision-making were centralized and rather simple. Central planners of the state projected the transmission investments along with the generation expansion. The transmission has acted as the highway of delivering electrical energy to the generation to the load. Traditionally, it was designed to meet the expected demand in the future within a region or a country while taking into account reliability issues. Main rationales for transmission investment were: technical reliability and economic efficiency, which often resulted in an overcapacity or lumpiness (Joskow et al., 2008). During the liberalization phase, the initial overcapacity and growth of privately-owned power generators helped develop the wholesale markets by trading across many counterparties (Brunekreeft et al., 2005; Pfeifenberger, 2012). This resulted in transmission capacity to be used efficiently to improve system reliability, to create liquidity, and to reduce market power.

In time, transmission investment has suffered from long lead times due to monopolistic nature of the infrastructure (Joskow and Tirole, 2005) and in many of the countries and regions, transmission capacity has not kept up with the demand growth and generation expansion. Another factor affecting the transmission investment has been the bottom-up nature of the planning process, although extensively studied (Kazempour, 2013), it has not helped with the real transmission investment problem that is faced today. What has been missed in those models was transmission planning conducted by utilities that do not consider regional integration (Lévêque, 2007). Therefore, transmission investment, although initially flourished the wholesale markets, now prevents further developments due to congestion issues, particularly between the markets and/or the regions. This has caused congested line failures and also cascading errors in voltage and frequency stability. To overcome these transmission investment hurdle, many solutions have been developed ranging from fully merchant (market) based forms to fully regulated forms (e.g., financial transmission rights –FTRs and physical transmission rights –PTRs), but none were efficient to keep up with the demand and new generation capacity (Pollitt, 2012; Rosellón et al., 2011; Wu et al., 2006). The major difficulty has always been to assess the cost/benefit measures of the investment process (Joskow et al., 2008; Chang et al., 2013). Although economic benefits and technical reliability parameters provided the main inputs for transmission planning prior to the liberalization period, many projects now have to account for the wide range of economic and/or public-policy benefits in the deregulated markets for increased competition and liquidity (Chang et al., 2013).

Along with the transmission investment challenges, today's electricity markets must address a number of key issues as follows:

i. Lowering air pollutant emissions (IPCC, 2014), although a recent study by Howarth (2014) argues that both shale gas and conventional natural gas have a larger GHG (Green House Gas) emissions than do coal or oil;
ii. deciding on investment and/or replacement in generation (i.e., coal power and/or nuclear power plants);
iii. deciding on investment and replacement in transmission system (Hogan, 1999);
iv. integrating renewable sources (Schumacher et al., 2009) and storage into their system (Pollitt, 2016);
v. increasing energy trading among countries by connecting markets (Newbery et al., 2016);
vi. increasing reliability upgrades and generation interconnection;
vii. overcoming congestion problems (Hogan, 1999);
viii. overcoming market design issues preventing coordination among countries (Imran and Kockar, 2014); and
ix. overcoming market design differences (Kassakian et al., 2011).

In the light of the aforementioned transmission investment challenges as well as the evolving electricity market and climate change requirements, there is a need for a radically new approach to reconsider the transmission investment from different perspectives that support the transition to a low-carbon energy economy. We think that all these common challenges, as well as the climate change policy constraints, can be overcome by a novel (top-down) approach to transmission investment strategy. In this context, REH is a transmission investment model to provide key insights to the policy makers in achieving a low carbon energy transition regionally.

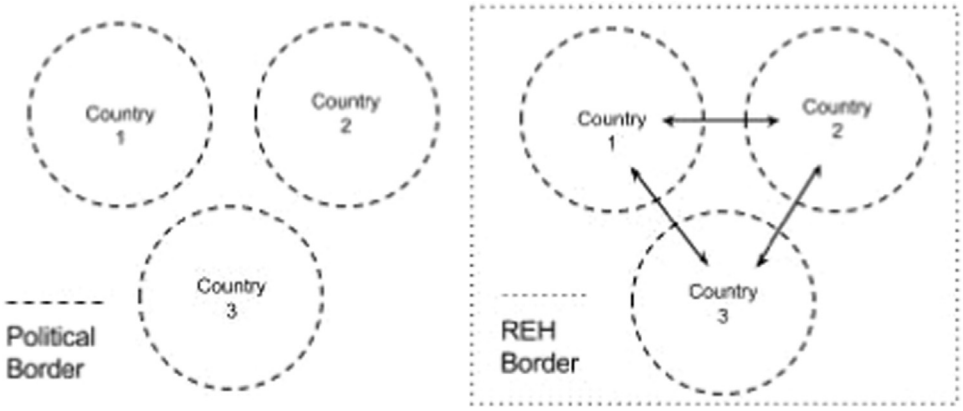

Fig. 1. REH concept: not connected (left) versus connected(right).

3. Why Regional Energy Hub?

3.1. Rationale

There are many useful attempts around the world towards creating a REH concept, but the framework and the parameters are not clarified for the hub or the region (Kassakian et al., 2011; Joskow et al., 2008; Bower, 2002). Many examples have been already moving in that direction, but without an appropriate definition for the REH. For instance, it is one of the European Union's objectives to create a single energy market by integrating regional energy initiatives (Puka and Szulecki, 2014; Dimitrova et al., 2016; ECF, 2010). Another study examines the use of Canada's clean electricity exports as a route to a better energy strategy for North American region (Nathwani, 2013). Tabors (2009) also shows the economics of change before and after connection in the Gulf Countries Council region, while Al-Asaad (2009) points out the creation of regional energy markets. Gadonneix et al. (2008) argue that "energy crises that have significantly dented economic growth in several Latin American countries could have been relieved if there had been adequate capacity and cooperation in the regional energy system". For the South East European region, Bajs (2003) studies the importance of the regional transmission system planning. Koritarov et al. (2004) investigate the economic and financial implications of regional energy interconnections in the South-Eastern Europe. Udrea et al. (2014) examine the optimal configuration of transmission corridor among countries Moldova, Ukraine and Romania. Khalfallah (2015) discusses that "A super grid connecting the two shores of the Mediterranean where it could help Europe meet its targets for integrating renewable energy". Kravtsov (2009) points out that the Central Asian countries Kazakhstan, Afghanistan, Uzbekistan are part of the Central Asia Regional Economic Cooperation Program, where transmission investments can link these countries in delivering electricity. Lawrence et al. (2006) discuss the Southern African Development Community where the region is endured with a lot of power generation potential, and integrated transmission expansion is the essential next step in bringing the economic efficiency to the region. Rana and Karmacharya (2014) point out that developing Nepal from land-locked state to a land-linked state would connect it with India by the cross-border transmission link. Chattopadhyay and Fernando (2011) argue that the improving cross-border trade by expanding on more transmission capacities in South East Asia would have economic, environmental and reliability benefits that can be captured under a new regulatory framework. Finally, Armar (2009) discusses creating regional power pools as a "how to kit".

It is clear that there have been many attempts in defining a framework for REH as outlined above. However, a generic framework would facilitate the investment process required for transmission expansion and hence, deliver the benefits regionally for the common challenges faced today.

3.2. Approach

We have developed a hypothesis for inter-TSO transmission investment (Joskow et al., 2008), where the investment is considered as strategic for all countries in the region rather than focusing purely on economic efficiency and reliability of the individual country. Such strategic investments would also ease decision for tactical investments (e.g., renewable energy investments) in these countries. Moreover, operational issues such as congestion within and neighboring markets can be relieved with additional transmission capacity. It would also allow large volumes of power exchange among countries.

In order to elaborate on what is discussed above, Fig. 1 shows three hypothetic countries/TSOs within the same region, but politically separated from each other. In Fig. 1 on the left, these countries are not physically interconnected, whereas on the right side of Fig. 1 they are interconnected by transmission lines.

It is assumed that each country in Fig. 1 has their unique fuel mix and demand characteristics, where country 1 with a "clean" fuel mix (i.e., there are no GHG emissions for its electricity generation within its political boundary), country 2 with a "dirty" fuel mix (i.e., substantial emissions exist for its fuel mix), and country 3 with a "partially clean" fuel mix (i.e., some "clean" and some "dirty") fuel mix. Also assume that all countries have unique seasonal and fluctuating demands.

Through this hypothetical example, it can be noted that the left side of Fig. 1 would not lead to a low-carbon energy economy neither on a country basis nor within the same region. When countries 1, 2, and 3 are not interconnected, fuel mixes used for electricity generation of each country is not optimized to reduce their emissions. However, right side of Fig. 1 may lead to a low-carbon energy economy either on a country basis or within the same region. When these countries are interconnected, overall emissions of the region can be minimized by using available and cleaner fuel mix of any country. Therefore, interconnected countries may be in a position to optimize their fuel mixes, since they rely on a common interest project in the same region as well as they strive for a low-carbon energy economy. Such a common interest project (e.g., interconnector or transmission investment) also provides generation flexibility, reduced GHG emissions, and access to renewables as described in Section 3. In this context, REH is a geographic area where the boundaries of the countries are not defined by the political borders, but defined by the potential electrical energy resources as shown in Fig. 1, in which all countries of the hub can jointly sustain. Hence, the REH hypothesis is that if the neighboring countries with mutually beneficial fuel mixes have common electricity market challenges and a common interest project such as a transmission investment, they can cooperate by considering the REH factors and then there can be a case for these countries to consider this transmission investment in transition to low-carbon energy economy.

In conclusion, we argue that transmission investment is one of the enablers that acts as a substitute or complementary to generation

Table 1
The REH framework.

Overarching Climate Change & Global Electricity Market Requirements Leading to Low-Carbon Energy Economy			
1. Geopolitical (broader alliance of countries, states or provinces towards low-carbon energy economy in a regional setting)	International Economics,Seamless Energy Markets,Climate Change with respect to Transnational Politics of Energy, Energy Market Regulations.	A list of indicators enabling the selection of countries leading to a formation of REH countries.	A region relies on trading than isolation.
2. Economic (use of mutually beneficial fuel mix and demand characteristics of countries, states or provinces in a regional setting)	Optimization of capacities regionally.	A list of functioning day-ahead electricity markets for the REH formed.	Reduced generation cost for the region.
3. Environmental (use of mutually beneficial fuel mixes of countries: dirty versus clean resources in a regional setting)	Optimization of emissions regionally rather than nationally.	A list of installed capacities in the REH formed.	Reduced GHG emissions for the region.
4. Financial (compare common interest projects with uncommon ones in a regional setting)	Optimization of financial resources towards a common interest project.	A list of projects with corresponding, IRR, NPV, ROA values in the REH formed.	Optimized adaptation strategies towards a low-carbon energy economy for the region.

investments (i.e., substitute for dirty fuel generation investments and complementary to clean fuel generation investments) and facilitates the solutions for the short-term (e.g., energy trading) to long-term (e.g., climate change) problems.

3.3. Benefits

Chang et al. (2013) indicate that today's transmission investment realities need to take into account all the short- to long-term benefits as well as regional considerations in order to extract the real value of the transmission investment shown in hypothetical example. One particular method that estimates the benefits among many transmission expansion projects by a cooperative game - Aumann-Shapley approach is provided by Banez-Chicharro et al. (2017). From that perspective, we propose a top-down REH approach where the most common benefits such as increased reliability, decreased transmission congestion, integrated renewables, reduced losses, reduced resource adequacy requirements, increased connection, and increased competition in power markets are included and more importantly idle capacities are regionally optimized towards a low-carbon energy economy. In this paper, a REH framework for transmission investment is proposed that can provide the following major benefits:

a) geographic: (i) increased connectivity, (ii) increased competition and consequently financial liquidity, (iii) flexibility for energy trading where common interests of countries are accounted in an integrated manner, and (iv) mitigation of weather and load uncertainty.
b) economic: (i) lower costs and consequently lower prices, (ii) generation flexibility by region's complementary fuel mix (different country fuel mixes to be pooled as a regional energy fuel mix) meeting peak consumption, and allowing access to lower cost generation, (iii) utilization of idle generation capacity within a region to compensate for the growing demand, (iv) substitution of capacities across generation and transmission facilities, (v) increased employment, increased economic activity, and (vi) reduced congestion due to improvements in transmission capacity.
c) environmental: (i) lower carbon-foot print in a region and mitigation of air pollutant emissions, (ii) enabling integration of renewable energy sources and distributed generation, (iii) exchanging for the cleaner form of electricity generation.
d) financial: (i) filtering the best investment alternative, and (ii) cost/benefit analyses and timing of project alternatives.

4. The REH framework

Based on the aforementioned, we propose the following REH framework depicted in Table 1.

4.1. Geopolitical parameter

The geopolitical parameter represents a broader alliance of countries, states or provinces where countries are geographically close or in different jurisdictions, but ultimately rely on trading rather than isolation. With the geopolitical parameter as an enabler, these countries or TSOs can benefit from increased trading in the same region where trading capacity is limited by existing interconnection (i.e., transmission) among the countries. However, today's energy geopolitics has been historically considered competitive / extractive in nature and mostly results in zero-sum games among the players (Austvik and Rzayeva, 2017), which may even halt trading among players in the long run.

Therefore, we propose that if geopolitics can be utilized to create a cooperative and inclusive field in the energy realm by utilizing the existing global institutional knowledge (deposited in agreements, platforms, connections and exchanges) to identify REH countries, the transition to a low-carbon energy economy would be more effective. We think that the global institutional knowledge has enough evidence in place to support this cooperation. Hence, investments into common projects, such as transmission investment, could be accelerated, which would result in further slowing down of the climate change effects. For this reason, we have developed a geopolitical parameter pertinent to the energy realm based on four drivers where it best represents the global institutional knowledge, and where we believe the most cooperation could occur in the optimization of a region's energy resources. These are (i) international economics, (ii) climate change with respect to transnational energy policies, (iii) seamless energy markets, and (iv) energy market regulations. Moreover, specific indicators can be developed out of these four fundamental drivers which would help forming a REH effectively.

4.1.1. International economics

With international trade barriers removed after the Second World War, goods and services have been traded across the borders around the world. The capital has followed the same suit and has financed the international trade since Bretton Woods (IMF, 2017).

With the globalization effect during the 1990s, this move has helped shape the markets, trade patterns, and financing needs around the

world. In fact, General Agreement on Tariffs and Trade (GATT) and World Trade Agreement have born in 1948 and evolved into World Trade Organization (WTO) in 1995 (WTO, 2017b).

In that sense, Weber and Peters (2009) argue that "Trade presents challenges to climate policy through carbon leakage and competitiveness concerns, but also potential solutions through the use of cooperative trade agreements, technology transfer, or carbon tariffs against recalcitrant nations." Therefore, we argue that institutional knowledge regarding international economics from international trade and finance perspectives are further developed since the 1970s and can be utilized to develop indicators for energy markets. In our study, we have adapted these indicators that show the range and direction of trade relationship. On one hand, the range can represent the existence of political union trade agreements or regional trade agreements, and on the other hand, it can indicate research studies advancing these regional trade agreements. We think that international economics is an externality that can be internalized while forming a REH.

4.1.2. Climate change with respect to transnational energy policies

United Nation's Framework Convention on Climate Change (UNFCCC) is one of the global institutional knowledge base that helps combat climate change by limiting average temperature increases. It has several essential parts. The convention, signed by 197 countries, is indicating that climate change and its adverse effects are well known by the parties. The Kyoto Agreement (the second part, which entered into effect in 1997 and signed by 192 countries) indicates that the signing parties agreed upon the emission reduction targets that are legally binding. The Paris Agreement (adopted in 2015 and ratified by 152 countries so far) also indicates that the convention's aim to "accelerate and intensify the actions and investment needed for a sustainable low carbon future". The convention's knowledge can be further developed for indicators to be used in energy markets. See UNFCCC (2017) for detailed information.

Similar to international economics, we have adapted indicators for a country advancing towards a low-carbon energy economy. In this case, the range can represent being a party to the convention or, on the other hand, being a party to the Paris Agreement. In this context, Keohane and Victor (2013) have argued that "the structure of international cooperation on some energy problems, such as climate change, is prone to deadlock. But by recrafting these problems –usually by making them "smaller" and focusing on the areas where national interests are better aligned for international cooperation– participating countries can avoid an impasse". Therefore, in this paper, we propose that climate change effects could be best attacked by investing into common challenges (i.e., national interests) regionally rather than nationally. In this case, the number of countries involved in that specific common project would be determined by the geopolitical parameter.

4.1.3. Seamless energy markets

Electricity markets around the world has liberalized, progressed and gathered institutional knowledge in the form of day-ahead, futures/forward or capacity markets. However, as the renewables deployment into electricity markets has increased, it has required a geographic coverage to obtain the least cost generation output out of the available energy sources. Particularly, without enough available capacity, transmission investment has lagged the generation expansion plans as it was originally designed for reliability, but not for the efficient use of resources in a region. Therefore, general electricity market challenges mentioned in Section 2 as well as in IEA (2010) need to be integrated systematically and regionally towards seamless operations as argued by Baritaud and Volk (2014); Boffa and Alessandro (2015).

Similar to indicators of climate change policies along with transnational energy policies, we have adapted indicators that would best reflect the direction of the development in the electricity markets, whether liberalization efforts take place in a specific country or there is an operational futures/forward market. An important issue in this case is that if there is an improving bilateral agreement in a trade relationship formed between parties, there is a possibility for building cross-border connectors as argued by Fischhendler et al. (2016). Also, if the trade has resulted in mistrust, then it is possible that an investment in transmission may not be implemented. In order to capture this perspective, we have included additional indicators showing whether there is already an investment plan for connector in place or not.

4.1.4. Energy market regulations

We have not adapted any indicators to reflect the institutional knowledge on market regulations as these are usually country specific. However, we argue that energy market regulations covering transparency platforms, financial regulations (whether physical or financial trades) and the role of institutions should be at least similar. More importantly, policies covering optimization of resources and actions on climate change should be inline regionally, but this is not the scope of this paper.

Essentially, the geopolitical parameter narrows down to identification of countries that can form a regional energy hub to allow the quantitative determination of the cost minimization and emission reductions through a model to show the benefits of transmission capacity. In this paper, this is performed through utilization of the indicators born out of aforementioned four drivers of geopolitical parameter. Detailed representation of these indicators will be depicted in the case study.

Hence, the geopolitical parameter is the first step in a feasibility assessment of additional transmission capacity that can utilize and optimize the energy resources of the whole region while promoting a low-carbon energy future.

4.2. Economic parameter

This parameter optimizes capacities of mutually beneficial fuel mix and demand characteristics of countries, states or provinces, regionally and ultimately leads to regional power generation cost reduction reflected in the corresponding functioning electricity markets.

4.3. Environmental parameter

This parameter optimizes emissions of mutually beneficial fuel mixes of countries, states or provinces regionally and ultimately leads to a regional emission reduction.

4.4. Financial parameter

This parameter optimizes financial resources towards a common interest project by comparing the net present value (NPV), internal rate of return (IRR) and real options analysis (ROA) of common interest projects with uncommon ones in a regional setting, and ultimately leads to an optimized adaptation strategies towards a low-carbon energy economy for the region.

Once the corresponding REH is selected and evaluated, a common interest project for the REH can be achieved. Overall net benefit from these REH factors would lead to an investment decision while unlocking the region's potential as a REH. In this context, we propose a formal definition of REH as follows:

> *Regional energy hub is an intersection point of all energy (electricity) supply and demand routes geographically originating, transiting, ending (centralizing) in a pre-defined region where there is an ultimate net benefit for that region from the following perspectives: geopolitical, economic, environmental, and financial. When the net benefit is evaluated (e.g., it is positive), there is a need for a transmission investment for that region.*

Table 2
REH case study: select a set of countries to form a REH.

1. Geopolitical Parameter: Which countries could benefit from the increasing trading?		Evidence Required	BG	TR	GR	RO
International Economics	1. Is there an indication of increased economic welfare after forming a regional trade agreement?	Existence of a study or negotiations under way. (0 or 1 point)	1	1	1	1
	2. Party to any trade agreement?	Existence of a WTO based or Regional economic integration organization (i.e. EU, NAFTA) agreement in place. (0 or 1 point)	1	1	1	1
Climate Change Policies with respect to Transnational	3. Party to UNFCCC?	Annex I. 1 Non-Annex I. 0 (0 or 1 point)	1	1	1	1
Politics of Energy	4. Ratified the Paris Agreement?	Yes. 1 No. 0 (0 or 1 point)	1	0	1	1
Seamless Markets	5. Is there a liberalization of electricity market act or an operating financial market in place? (any applicable one)	Any, 1; Non, 0.	1	1	1	1
	6. Is there a liberalization of gas market act or an operating financial market in place? (any applicable one)	Any, 1; Non, 0.	1	1	1	1
	7. Electricity- Interconnector?	Any, 1; Non, 0.	1	1	1	0
	8. Gas - Interconnector?	Any, 1; Non, 0.	1	1	1	0
Common Project(s)	9. List any common project being considered but not undertaken yet?	Any, 1; Non, 0.	0	0	0	1
Geopolitical Parameter - Outcome	10. Outcome		8	7	8	7

5. REH case study: Romania-Turkey interconnector

A recent study regarding a subsea cable between Romania and Turkey had been completed (Güler et al., 2013). This project has been rejected due to economic unfeasibility, i.e., only considering market price differences between the two countries. In this case, the transmission investment was only evaluated based on the benefits of the strategic interconnection capability between the countries and the arbitrage opportunities arising from price differences between the markets (Newbery et al., 2016). However, it could have arisen as a common interest project to support the transition to a low-carbon energy economy in the region. In the context that transmission may complement generation (Lévêque, 2007), this transmission investment project could have been implemented and it might have replaced a coal power plant investment planned in the region. Then, the transmission project would not only be able to mitigate emissions (or decrease carbon costs), but also more interconnection could have enabled the utilization of the idle capacity in the region. Moreover, it could have also enabled the optimization of the regional electrical energy sources where transmission could be a substitute for generation sources (Lévêque, 2007; Hooper and Medvedev, 2009).

Tables 2, 3 show the REH framework applied to four countries: Bulgaria (BG), Greece (GR), Romania (RO) and Turkey (TR), i.e., the REH Countries. In this case study, Turkey and Romania (TR-RO) subsea interconnector is considered as a common interest project, which was found unfeasible due to the previous investment selection method (i.e., only based on market price differentials).

Table 2 shows the geopolitical parameter indicators developed in Section 4 and they are evaluated for the aforementioned countries with a simple grading system (e.g., 0 or 1 point). The objective of this grading is to indicate / gauge the REH readiness such that the hypothetical REH countries shown in Fig. 2 would have same or closer grade points. With this method, we think that the geopolitical parameter table can be universally applied for developing potential REH(s) around the world. Table 2 gives the details on the evidences for the REH in question as follows.

From international economics point of view, indicators show evidence of a potential regional trade agreement benefiting REH countries, particularly Greece and Turkey, as argued by Kocaslan et al. (2014). Hence, one point is given to each country indicating the existence of a regional study. Also, WTO publishes a list of regional trade agreements among REH countries in their corresponding database in WTO (2017a). In this case, one point is given to each country, since there is a bilateral or a regional economic integration agreement (e.g., European Union) in

Fig. 2. REH case study: Bulgaria (BG), Greece (GR), Romania (RO), Turkey (TR).

Table 3
REH case study: select a set of countries to form a REH.

2. Economic Parameter. Do these countries have functioning electricity markets (intra-day, day-ahead markets) that could reflect increase in social welfare or decrease in generation costs?
BG - Independent Bulgarian Energy Exchange, IBEX
GR - Operator of Electricity Market - LAGIE
RO - Romanian Gas and Electricity Market Operator, OPCOM
TR - Energy Exchange Istanbul, EXIST
3. Environmental Parameter. Do these countries have fuel mixes that are beneficial to eliminate emissions environmentally?
Table 4 shows region's clean energy fuel mix vs. dirty one.
53,019 out of 120,378 MW total installed capacity is clean energy.
4. Financial Parameter. Do these countries have a portfolio of common interests that need to be invested in financially?
TR-RO Transmission Investment.

place among the REH countries.

From the climate policies perspective, indicators show evidence related to the UNFCCC participation indicated by one point in the table as well as one point for ratification information related to the Paris Agreement (UNFCCC, 2017).

From the seamless markets point of view, a list of energy (power and gas) exchanges in REH countries is published at the Association of European Energy Exchanges member website given in Europex (2017). We have graded the existence for each electricity and gas markets as one point.

Furthermore, evidence showing an existence of a physical electricity interconnection can be found at the European Network of Transmission System Operators for Electricity (ENTSO-E) Transparency Platform under the transmission cross-border flows at the border-country level (ENTSO-E-TP, 2017a). Accordingly, we have graded the existence of a connection from/to each country as one point regardless of the number of lines. Therefore, each BG-TR, TR-GR, GR-BG, and RO-BG connections are given one point, whereas each RO-TR and RO-GR connections are given zero point.

Similarly, evidence showing an existence of a physical gas interconnection can be found at the European Network of Transmission System Operators for Gas (ENTSO-G) Transparency Platform under the transmission cross-border flows at the border-country level (ENTSO-G-TP, 2017). Similar to grading for electricity connections, we have graded one point for each BG-TR, TR-GR, GR-BG and RO-BG connections, whereas zero point is given to each RO-TR and RO-GR connections.

Table 3 shows the economic, environmental, and financial parameters applied to the REH countries formed in Table 2. For further clarification, economic parameter regarding the existence of a functioning electricity market given in Table 2 is not repeated here. It merely shows that the countries have already developed their markets.

In the subsequent sections, a mathematical framework for this REH case study is developed.

6. A Model for the REH framework

In Fig. 2, the transmission line connections between the countries of the REH are displayed and each node (i.e., bus) represents a country in the REH (i.e., there is no detailed representation of countries' transmission systems). Power imports/exports of the countries from/to other countries outside of the REH are not considered, but it can be easily incorporated into the model. Although financial constraints are not modeled at this stage of the study, the role of financial constraints, i.e. debt, is central in structuring such major infrastructure projects. As Tverberg (2015) discusses, inability to originate financial resources for energy projects could create significant problems in energy supply security.

Sets and indices

- $i \in N$ set of buses (countries): BG, TR, GR, RO
- $j \in N_i$ set of buses connected to bus i
- $h \in H$ set of generation technologies: nuclear, coal, hydro, gas, renewables
- $m \in M$ set of time blocks: peak, intermediate, base

Parameters

- c_h^G Cost of generation by technology h, \$/MWh
- $c_h^{CO_2}$ Cost of emissions by generation technology h, \$/MWh
- d_{mi} Demand at each bus i for time block m, hundred MW
- B_{ij} Susceptance of each transmission line connecting buses i and j, per unit (p.u.)
- $f_{ij}^{min}, f_{ij}^{max}$ Minimum and maximum of flow limits on transmission line connecting buses i and j, hundred MW
- g_{ih}^{max} Maximum power output of generation technology h at bus i, hundred MW

Variables

- g_{ih} Generation by technology h at bus i, hundred MW
- θ_i, θ_j Bus angle at buses i and j, radian
- γ Dual variable for reference bus constraint
- $\rho_{ij}^{min}, \rho_{ij}^{max}$ Dual variables for flow limit constraints
- λ_i Dual variable for energy balance at each bus i (i.e., nodal price), \$/MWh
- ϕ_{ih}^{max} Dual variable for maximum generation output constraint

The mathematical notation and the model for the REH framework are as follows (dual variables are in []):

$$\min_{g_{ih},\theta_i} \sum_{i\in N}\sum_{h\in H}(c_h^G + c_h^{CO_2})g_{ih} \tag{1}$$

s.t.

$$\sum_{h\in H} g_{ih} - d_{mi} = \sum_{j\in N_i} B_{ij}(\theta_i - \theta_j) \quad [\lambda_i] \quad \forall\ i \in N \text{ and } m \in M \tag{2}$$

$$-f_{ij}^{min} \le B_{ij}(\theta_i - \theta_j) \le f_{ij}^{max} \quad [\rho_{ij}^{min}, \rho_{ij}^{max}] \quad \forall\ i \in N \text{ and } j \in N_i \tag{3}$$

$$\theta_{GR} = 0 \quad [\gamma] \quad \text{reference bus} \tag{4}$$

$$g_{ih} \le g_{ih}^{max} \quad [\phi_{ih}^{max}] \quad \forall\ i \in N \text{ and } h \in H \tag{5}$$

$$g_{ih} \ge 0 \quad \forall\ i \in N \text{ and } h \in H \tag{6}$$

$$-\pi \le \theta_i \le \pi \quad \forall\ i \in N \tag{7}$$

The objective function (1) of this model minimizes the total of the generation and emission costs. Constraints (2) is the energy balance at each bus, where the dual variables represent the electricity prices at each bus and constraints (3) are the power flow limits through transmission lines, where flows are modeled according to the linear DC flow assumptions for simplicity and tractability (Gabriel et al., 2012). Constraint (4) defines the reference bus as GR and constraints (5) are for the maximum power outputs for each generation technology and country. Finally, non-negativity constraints for generation are modeled by constraints (6) and bus angle limits are represented by (7). Clearly, the model is a linear programming (LP) problem that can be solved very easily using the state of the art LP solvers (e.g., CPLEX).

As described in Section 2, utilizing REH approach for novel transmission investment strategies could reduce countries' carbon emissions. It can facilitate integration of renewables and also release congestions. In order to better assess the impact of transmission investment between Romania and Turkey, we have discretized the load-duration curves using several demand blocks. We have modeled the yearly demand, by three load blocks (denoted by m) using the base, intermediate (mid) and

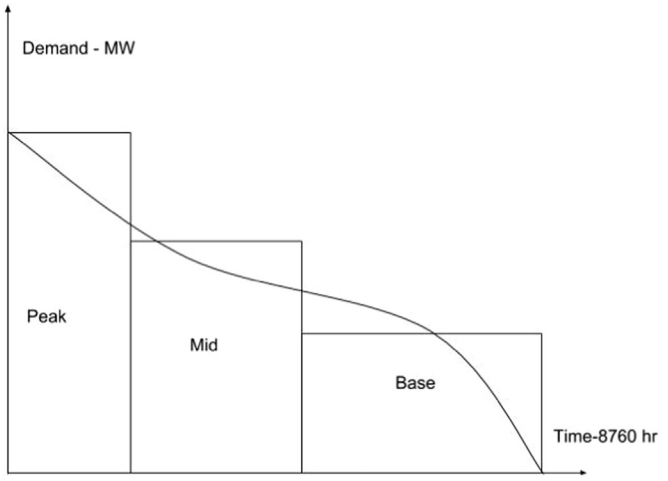

Fig. 3. Discretized load-duration curve.

peak hours of a typical load-duration curve at bus *i*. Baseload is a permanent load and is generally supplied by nuclear and coal power generation. Intermediate and peak loads are the average and maximum loads, respectively, and are usually satisfied by flexible power generation such as gas and hydro.

6.1. Assumptions

Traditionally, transmission investment assessment studies are conducted for a target year, e.g., using target year's load-duration curve or its approximation (Kazempour, 2013). In our REH approach, instead of a target year load-duration curve, we have utilized a discretized load-duration curve for each bus in the recent year in order to make an assessment for the transmission investment feasibility. We have done this to see whether a regional energy trading opportunity could have been enabled by a potential transmission investment for the REH in question or not. The use of this model for realistic purposes would require careful forecasts for both generation and demand in the target year. In Fig. 3, a typical annual load-duration curve is depicted and it is discretized by using three time blocks (peak, intermediate, and base). We assume that peak, intermediate and base loads appear, 20%, 35% and 45%, respectively, of total hours in a year (i.e., 8,760 h). This corresponds to 1,752 peak load hours 3,066 intermediate load hours and 3,942 base load hours. Consequently, we have assumed the following load factors: 1.0 (peak), 0.70 (intermediate), and 0.50 (base).

6.2. Data

The model concentrates on the generation and emission cost minimization of the REH countries selected. Table 4 presents the breakdown of the REH countries' installed capacity by generation technology in 2015 (ENTSO-E-TP, 2017b). It also shows the peak demand values for Bulgaria, Greece, Romania (EUMarkets, 2014) and Turkey (TEIAS, 2015). Table 5 shows the marginal generation and emission costs of the installed capacity per technology assumed for this study (IEA, 2010), and our assumptions on capacity factors. Finally, Table 6 presents the data related to the transmission system (Gabriel et al., 2012; ENTSO-E-TP, 2017a).

Table 5
REH generation parameters per technology.

REH	Nuclear	Coal	Hydro	Gas	Renewable
Generation Cost ($/MWh)	24	25	6	65	22
CO_2 Cost ($/tonne)	0	24	0	11	0
Peak capacity factor	0.80	0.50	0.75	0.65	0.35
Mid-peak capacity factor	0.85	0.75	0.45	0.40	0.25
Base capacity factor	0.95	0.75	0.25	0.10	0

Table 6
Transmission line parameters.

Line #	From	To	Susceptance - B_{ij} (p.u.)	Capacity (MW)
1	BG	TR	1,000	500
2	BG	GR	1,250	800
3	TR	GR	1,500	500
4	BG	RO	1,500	500
5	TR	RO	1,500	500

Table 7
REH power flows before and after transmission investment based on discretized load-duration curve ("-": 0%, "NA": not applicable).

REH Power Flows		BG-TR	BG-GR	TR-GR	BG-RO	RO-TR
Peak	Before (MW)	−442	−136	500	−500	–
	After (MW)	−373	−205	313	−500	−59
	Change	−16%	51%	−37%	–	NA
Mid	Before (MW)	500	800	210	500	–
	After (MW)	500	800	210	250	500
	Change	–	–	–	−50%	NA
Base	Before (MW)	500	541	−101	500	–
	After (MW)	500	712	104	250	500
	Change	–	32%	−203%	−50%	NA

6.3. Results and discussion

The LP models for different demand blocks are solved using CPLEX under GAMS (2015) on a Windows-based personal computer with a processor at 2.4 GHz and 8 GB of RAM. The transmission investment simulated between Romania and Turkey resulted in a cost-effective fuel mix switching among REH countries. This ultimately reduced generation costs and emissions for these countries due to the fact that low cost/emission generation technologies are utilized. Table 7 presents the results of power flows among REH countries before and after transmission investment. It can be observed that in base- and mid-load blocks, there are net power flows from Romania to Turkey in the amount of 500 MW. On the other hand, there is a net power flow of 59 MW from Turkey to Romania in the peak load block. Note that negative values in Table 7 depict the power flows in reverse direction and these flows are governed by the Kirchhoff's Laws of current and voltage. In the peak demand case, the Kirchhoff's laws do not allow any net flows from RO to TR, but from TR to RO only. Hence, this reduces the generation by coal plants by

Table 4
REH installed capacity (MW) and peak demand (MW).

REH Capacity	Nuclear	Coal	Hydro	Gas	Renewable	Total	Peak Demand
BG	2,000	5,648	2,965	19	653	11,285	7,967
TR	–	15,226	23,664	25,643	4,345	68,878	41,002
GR	–	4,459	3,149	5,631	4,386	17,625	9,894
RO	1,298	5,872	6,470	4,861	4,089	22,590	8,627
REH (Total)	3,298	31,205	36,248	36,154	13,473	120,378	67,490

Table 8
Change in REH capacity utilization (after *minus* before transmission investment in MW, percent changes in parentheses).

REH Capacity Change		Coal	Gas
Peak	BG	0	0
	TR	0	−197 (−1%)
	GR	0	256 (8%)
	RO	−59 (−3%)	0
Mid	BG	−250 (−6%)	0
	TR	0	−500 (−10%)
	GR	0	0
	RO	750 (149%)	0
Base	BG	−79 (−3%)	0
	TR	0	−295 (−11%)
	GR	0	−376 (−100%)
	RO	750 (78%)	0

Table 9
REH costs (before and after transmission investment).

REH Cost ($/hour)		Generation	CO_2	Total
Peak	Before	1,893,075	602,672	2,495,747
	After	1,895,451	603,445	2,498,896
	Difference	2,376	772	3,149
	Change	0.13%	0.13%	0.13%
Mid	Before	1,070,841	341,451	1,412,292
	After	1,050,841	334,951	1,385,792
	Difference	−20,000	−6,500	−26,500
	Change	−1.87%	−1.90%	−1.88%
Base	Before	785,927	275,273	1,061,200
	After	759,090	266,551	1,025,641
	Difference	−26,837	−8722	−35,559
	Change	−3.41%	−3.17%	−3.35%

59 MW. In the peak demand case, the feasibility of the solution is satisfied by higher generation/emission costs.

The dual variable for the power flow constraints (e.g., ρ_{ij}^{min} or ρ_{ij}^{max} depending on the flow direction) shows the value of the unit MW increase in the new transmission line capacity (i.e., marginal value of transmission line capacity). It is found to be $53/hour for both base- and mid-load demand blocks, where the full capacity of the new RO-TR line is used. In the peak demand case, as the capacity of the line is not fully utilized, it is zero. A future extension of this study may consider the capacity size of the new transmission line as a decision variable in the model, where optimal capacity size is also determined by the model. But this would require a new modeling approach, i.e., an equilibrium model, which is out of the scope of this study and left for future research.

Table 8 presents *the net* change in fuel mix *(installed capacity)* of each REH country (after minus before transmission investment), complying with the objective of the REH model, e.g., minimizing generation costs and emissions for the overall region. Note that there are only changes in capacity utilization of coal and gas generation, whereas there was no change in the capacity utilization of nuclear, hydro, and renewable generation. This suggests that the new transmission line between Turkey and Romania exchanges fossil-fuel based gas generation with cheaper coal generation. This has not only reduced the costs of generation but also the emissions with the flexibility enabled by the new transmission capacity. Table 9 shows the associated cost and emission reductions as a result of this fuel switching.

For the peak-load block, hourly generation and emission cost figures have increased by 3,149 $/hour. On the other hand, for the base- and mid-load blocks, hourly generation and emission cost figures have decreased by 26,500 $/hour and 35,559 $/hour, respectively. Additionally, overall annual cost savings can be estimated from these figures using the number of hours per load block:

$$(26{,}837*3{,}942) + (20{,}000*3{,}066) - (2{,}376*1{,}752) \approx 160\ Million\ \$/year \quad (8)$$

It should be noted that new transmission investment among REH countries would reduce power generation costs and emissions. Also the REH method can integrate countries in such a way that transmission investment would create ultimate benefits for each REH country.

7. Conclusion and policy implications

In this paper, we have utilized a geopolitical parameter to select a set of countries to form a regional energy hub. We have utilized the economical parameter to minimize cost and the environmental parameter to reduce CO_2 emissions simultaneously in the newly formed REH's total energy fuel mix. The preliminary results for TR-RO case study indicated that the total cost minimization approach for the region results in a net benefit in favor of the transmission investment. The REH enables transmission capacity to achieve reduced cost generation and emissions by physically interconnecting markets in a predefined region, essentially enabling fuel switching of carbon based power generation. We have introduced a formal definition of the REH and presented a conceptual framework for the REH development including the underlying mathematical model.

As a future research for the REH framework, we plan to employ real options analysis to generate low carbon energy-economy adaptation strategies by benchmarking transmission investment against many options: renewables, gas, coal, nuclear, hydro pump storage, geothermal, storage, and demand side management. We expect that given an investment time horizon of 5–10 years, a region should be able to identify and consider an adaptation strategy in their corresponding REH framework. In our view, the framework will act as a platform to explore feasible options. Hence, we expect that transmission investment could be a key enabler of renewable energy, which will profit by accessing to transmission in remote locations where demand is not in proximity.

In conclusion, REH framework would be an important energy policy instrument to evaluate the readiness (or effectiveness) of countries in reaching low-carbon energy economy as a region collectively. Hence, it can also accelerate country's decision towards becoming less carbon intensive by determining clear policy options among many. Therefore, we think this method can also be applied as a feasibility platform to selected regions around the world.

Acknowledgements

The authors would like to acknowledge that J. Nathwani, Ontario Research Chair in Public Policy for Sustainable Energy, is supported by the Ontario Council of Universities (COU) through an endowment to the University of Waterloo.

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